Practicability Issues of Sensor-Based Damage Detection on Military Platforms

Klaus-Peter Kress
KT-Systems GmbH
Ringstr. 19
97502 Euerbach
GERMANY

Klaus-peter.kress@ktsystems.de

ABSTRACT

A broad variety of military platforms such as fighter aircraft are nowadays operated for several decades under sometimes varying missions. Additional requirements resulting from more severe fatigue spectra or extended life for these platforms or improved performance requirements for future platforms may require additional means of ensuring structural integrity. It is then important to gain the maximum usage (fatigue life / load levels) of aircraft components most efficiently still ensuring structural integrity at all times.

Conventional structural health monitoring systems are typically based on loads and usage monitoring. Together with modern non destructive damage detection techniques it is possible to safely operate even aged platforms or enable operation of otherwise impossible designs. This goal is achieved by periodic examinations in order to ensure that a structural item is free of damage. However, the dismantling of structures for the purpose of non destructive testing may be very costly, time intensive and sometimes harmful to the surrounding structure itself (accidental damage, unplanned cut-outs for post-inspection, etc.). Therefore, a practical sensor-based damage detection and monitoring system requires integrated, reliable and affordable sensing systems that are needed to avoid disassembly where economically or technically justified.

The practicability aspects associated with the introduction of health monitoring sensors to existing and future military platform structures are related with integration aspects and the advantages/disadvantages of permanent installation on board.

As an example, such introduction aspects are applied to the Smart Wide area Imaging Sensor System (SWISS) Technology that serves to detect, localise and size material defects with small, highly integrated, weight and volume saving ultrasonic sensors without need to access the damage susceptible area.

INTRODUCTION

A broad variety of military platforms such as fighter aircraft are nowadays operated for several decades under sometimes varying missions. Additional requirements resulting from more severe fatigue spectra or extended life for these platforms or improved performance requirements for future platforms may require additional means of ensuring structural integrity. It is then important to gain the maximum usage (fatigue life / load levels) of aircraft components most efficiently still ensuring structural integrity at all times.

Conventional structural health monitoring systems are typically based on loads and usage monitoring. Together with modern non destructive damage detection techniques it is possible to safely operate even aged platforms or enable operation of otherwise impossible designs. This goal is achieved by periodic

Kress, K.-P. (2006) Practicability Issues of Sensor-Based Damage Detection on Military Platforms. In *Multifunctional Structures / Integration of Sensors and Antennas* (pp. 8-1 – 8-10). Meeting Proceedings RTO-MP-AVT-141, Paper 8. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Report Documentation Page

Report Documentation Page	Form Approved OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 OCT 2006	**N/A**	**-**

4. TITLE AND SUBTITLE	
Practicability Issues of Sensor-Based Damage Detection on Military Platforms	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **KT-Systems GmbH Ringstr. 19 97502 Euerbach GERMANY**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202433., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

examinations in order to ensure that a structural item is free of damage. However, the dismantling of structures for the purpose of non destructive testing may be very costly, time intensive and sometimes harmful to the surrounding structure itself (accidental damage, unplanned cut-outs for post-inspection, etc.). Therefore, a practical sensor-based damage detection and monitoring system requires integrated, reliable and affordable sensing systems that are needed to avoid disassembly where economically or technically justified.

A quick overview on selected damage detection systems is discussed in [1]. More detailed literature for each is found in [2] to [7].

Hardly accessible areas that are expected to be susceptible to damage often require most powerful NDT techniques such as ultrasonic inspection in order to reduce disassembly of concerned parts. Even for exterior structure, such as riveted joints or integral composite structures, ultrasonic inspection techniques are applied to detect various types of sometimes barely visible damage types. Especially military platforms nowadays incorporate numerous innovations that emerged from material sciences and modern structural design to increase structural efficiency. The more complex the material properties, the geometry and size of the structure are - the more powerful NDT techniques are necessary. For conventional inspection it is sometimes economically feasible to afford expensive techniques such as imaging ultrasound (e.g. phased arrays), eddy current arrays or even x-ray (e.g. mobile systems), but most often these techniques still require considerable disassembly of the military platform. An example for evaluating the possibility of fatigue life exploitation by means of integrated imaging ultrasound can be found in [8].

Only permanently integrating (bonding) sensors and interfacing such sensors within the platforms infrastructure (cabling, connectors, antennas, etc.) allows remote interrogation and elimination of otherwise disassembly intensive conventional inspection.

The impact of number of inspected parts versus the number of sensors

Still such integrated sensor systems must have a comparable quality of health data as conventional inspection methods. The performance quality of conventional NDT sensing techniques is often related to number of channels, accuracy, speed, range, coverage, real-time interpretation and broad applicability for different parts and materials. High procurement and operation cost for powerful NDT technology may be affordable if the same equipment is used for a large number of structural inspections (similar parts on many platforms and many different parts per platform). Simply copying such technology and permanently applying it to each structural part that needs to be inspected would cause huge life time costs per part and make it unlikely to reduce cost compared to existing conventional inspection alternatives.

Expected/Unexpected Damage – Conventional NDT versus permanent installed sensors

If an integrated sensor-system is to be a better alternative to conventional inspection, it must have similar or higher quality and result in significant lower life time costs of the platform’s inspected structure. And we have to keep in mind that conventional inspection – including visual inspection during disassembly – is sometimes very powerful compared to installed sensors whose damage detection coverage is typically strongly limited. A lot of unexpected damages have been detected in the past by visual inspection or audible acoustic emissions. Simply extrapolating existing NDT sensor technology to integrated sensor-based structural health monitoring would inflationary increase the number of permanently installed sensors to include the whole conventionally covered area. Such approach would definitely question the affordability and introduction in practice.

The practicability aspects associated with the introduction of health monitoring sensors to existing and future military platform structures are related with integration aspects and the advantages/disadvantages of permanent installation on board.

As an example, such introduction aspects are applied to the Smart Wide area Imaging Sensor System (SWISS) Technology that serves to detect, localise and size material defects with small, highly integrated, weight and volume saving ultrasonic sensors without need to access the damage susceptible area.

EXPECTED/UNEXPECTED DAMAGE – PERFORMANCE REQUIREMENTS

Even conventional inspections typically require a priori knowledge of possible damage details in order to be able to reliably detect damage, e.g.

- In which material (isotropic, anisotropic, cast, extruded, prepreg, fabric, …)
- In which area/geometry (skin, plate, shell, volume, …)
- Surface – Subsurface – Embedded flaws?
- Size (crack length and surface geometry, delaminating surface and size, …)
- Orientation (crack orientation with respect to parts boundaries)

Before or during the time of applying conventional techniques for inspection a lot of care is taken to exclude influence of parameters, e.g. calibrating the equipment for given conditions (hangar temperature, trials on reference material parts before and after testing, etc.). Sometimes adapters or automatic positioning equipment is used in order to achieve repeatability and comparability of measurements.

Due to space constraints and complexity of design, especially on military platforms, small NDT probes have great advantages in detecting expected and unexpected damages, but the probes need to be moved and may require coupling media.

A permanent installation of sensors needs to replace the position possibilities of conventional probes, at least partly. In practice it would mean to cover most of the inspected structure with sensors or adapters leading to weight penalty and susceptibility to failure.

In the following we focus on the state of the art phased array ultrasound technology because it largely covers the above mentioned inspection requirements (different materials, location of damage, size and orientation). A more detailed view can be found in [8].

The phased array ultrasound approach uses a selection of temporarily surface coupled actuator- (sensor-) elements to excite specific ultrasound waves in such a controlled, phase correlated way that their wave interference in the structure allows focusing the propagating ultrasound field to test points that are to be checked for damage. A change of the acoustic impedance of the material due to local loss of stiffness and/or change in density at the test point cause the ultrasound wave to be scattered. The scattered field is then analysed by the receiving selection of sensor (actuator) elements to yield information about location and size of damage with respect to the probes current position. The scanning of a volume of test-points is typically performed in real-time to provide immediate feedback to the NDT operator while the probe is moved or positioned.

The relative position of elements in a phased array probe is typically fixed and specific for tuning the parameters with which the phased array equipment is running the whole probe. This arrangement is taken into account within the equipment to optimise the scanning process and speed-up the hard- and software to achieve real-time feedback. Generally the "coverage/range/resolution" performance of the system for a given structural part depends on the settings of channels/sensor-elements/signal-noise-ratio/bandwidth/ memory-depth of probe and equipment.

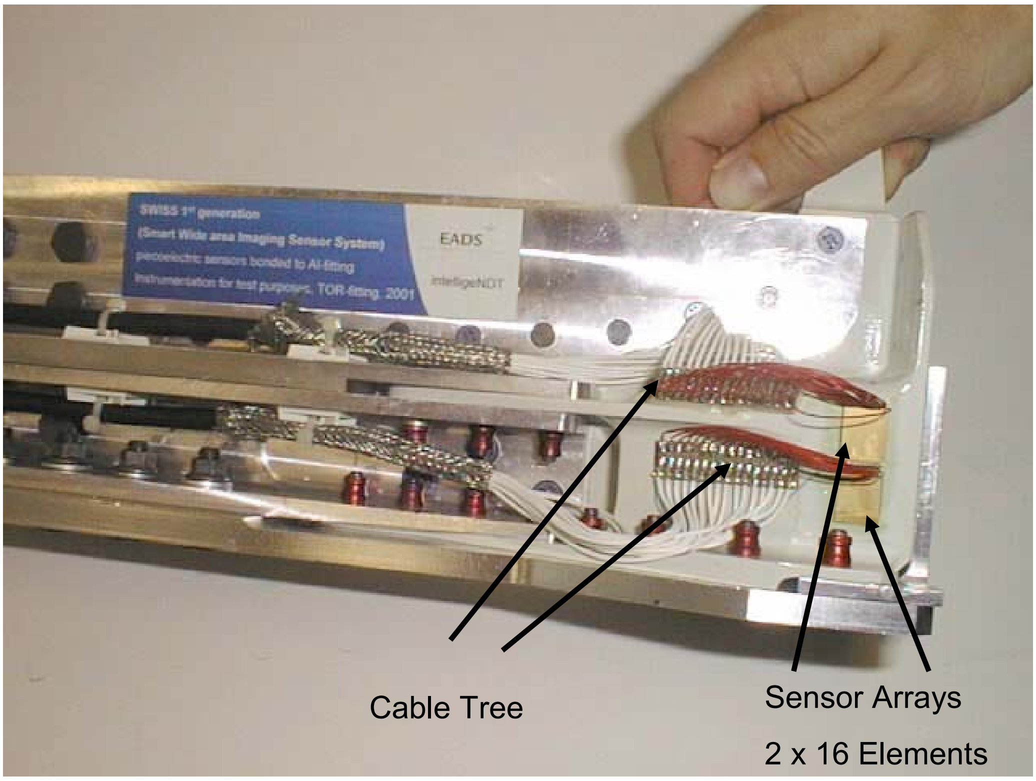

Figure 1: Structural part, expected to be fatigue susceptible. Result of testing: no expected damage for multiples of originally expected lifetime. A permanently bonded sensor array detected unexpected damage in unexpected, hidden (over-bolted) area at a distance of about 80mm left to the sensor arrays.

Imagine applying state of the art phased array technology for sensor-based permanently integrated damage detection. An example of such integrated-sensor approach is shown for the case discussed in [9] in Fig. 1. Even though the sensor instrumentation is pretty small the cabling looks like a nightmare.

The positive aspects of phased array –

- The physics of phased array ultrasound in metallic and composite materials is well known.
- Huge experience with damage detection and qualification of NDI processes is available.
- The imaging provides best diagnostic capability and data to assess damage for optimised repair schemes or to justify deferred maintenance.

The draw-backs of existing technology are obvious:

- The permanent bonding becomes vital to the system performance.
- Much more sensor elements are necessary to cope with lack of repositionability.
- Too high operating voltages (up to 300V).
- Too much cabling / connector pins and associated weight.
- Too much equipment hardware.
- Too high costs per structural part.

To introduce such health monitoring sensors to existing and future military platform structures would inevitable cause practicability problems in terms of integration and maintenance of very costly, heavy and spacey technology.

For the development of a sensor-system that is to be permanently integrated into the platform we wish to keep the positive aspects mentioned above while eliminating the draw-backs.

PERMANENT INSTALLATION – DISADVANTAGE BECOMES ADVANTAGE?

Permanent Installation at First Glance

At first glance the permanent installation of sensors seems to be a big hurdle against introducing health monitoring techniques. Engineers and customers doubt the reliability of such installations – with good reason.

Therefore it is very important to

- Increase the reliability of sensor-bonding - processes of integration, e.g. retrofit-bonding or embedding.

While numerous improvements to the sensor-bonding process have been achieved in the past – in terms of surface preparation, adhesives, contaminations, etc. – still the permanent installation of sensors remains an invasive action to the structure and the installed, overall reliability is often not yet satisfactory.

Therefore it will be for long as important to

- Implement self-test capability of the system that covers the continued integrity of the sensor-bond.

In the case of the imaging ultrasound technology SWISS the overall system function critically depends on the sensor-bond, because a degradation of the bond would reduce coupling of ultrasound waves into the structure. However, due to the imaging capability the system is able to localise ultrasound echoes not only stemming from damage, but also emerging from natural boundaries of the structural part, e.g. edges, corners, bolt holes, etc.. If the bond quality degrades such natural echoes (also sometimes called geometrical shape echoes) would gradually disappear. But since the part and its boundaries cannot disappear, such change in the ultrasonic image would clearly indicate system failure and thereby provides the above requested self-test capability. Figure 2 shows an example of how this self-test works in practice for a two-dimensional monitoring task.

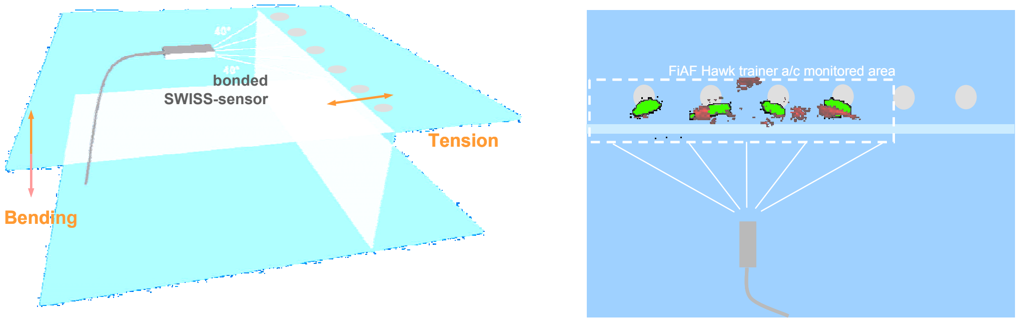

Figure 2: Left: surface mounted SWISS sensor (piezo-array) monitors riveted metal skin in hidden, inaccessible area for bending or tension cracks. Right: US image shows (green) natural rivet hole echoes proving system is working and (red) fatigue crack echoes.

For conventional array probes it is difficult to use natural echoes as self-test on the actual inspected part, because the position of the probes may change slightly and the echo accordingly. Unless one uses special adapters the ultrasound data of two different measurements is difficult to be compared accurately. Most often the "calibration" and quality prove of conventional probes is done by using reference parts with defined echoes before and after the actual inspection.

In our case when the sensor is permanently bonded the position of sensor does not change any more, which allows accurately comparing natural echoes from inspection to inspection. Together with the high phase resolution it is possible to exploit the accurate sensor elements position and detect even small deformations in hidden areas of a structural part due to the change of natural echoes´ phase positions.

Figure 3 shows an example of massive aluminium for which phase information from echoes is displayed.

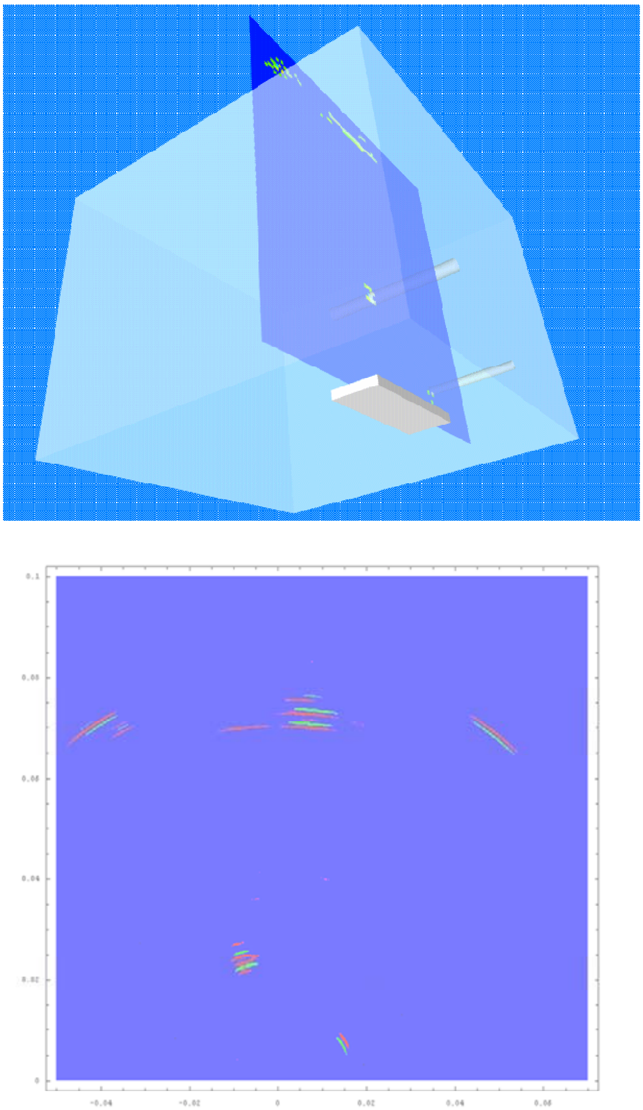

Figure 3: Upper: SWISS sensor applied to the bottom of massive aluminium incorporating two hidden defects, a back wall and two corners. Lower: ultrasound image with phase information of echoes – sensor middle equals (0,0), unit: meter. Practical accuracy to detect deformations in hidden areas by moved natural echoes ~ 0.1 mm.

Permanent Installation at second glance

At a second glance we may ask whether it is possible to identify positive aspects of the permanent installation to overcome some of the draw-backs mentioned above: number of sensor elements, operating voltages, cabling / connector pins and associated weight, equipment hardware and consequently high costs per part.

Number of Sensor Elements

Typical array probes in imaging ultrasound have between 16 and 512 elements. The high number is necessary to achieve not only high resolution and coverage. Often cracks are very “stealthy” with regard to a single element probe, if the crack plane is in parallel with the line of sight from the probe to the damage. The high number of elements is also to maximise the surface aperture of the probe to provide maximum perspective with regard to the defect’s possible orientation and its ultrasound scatter characteristic.

Since the sensors are relatively small it seems quite feasible to achieve a similar number of elements for permanently installed sensors. To ease installation the number of sensors should be variable with the available instrumentation surface on the concerned structural part. Therefore we developed a multi-sensor front-end for which the number of sensors is easily adaptable.

Operating Voltage

The high operating voltage of conventional probes is normally advantageous to achieve high signal-to-noise-ratio and achieve real-time feedback. But if we only wish to do an inspection it does not really matter whether it takes 10 milliseconds or 10 minutes. All other processes associated with such inspection can take much longer. Since the position of permanently installed sensors does not change, the result of several measurements during the same inspection is supposed to be the same. By increasing the number of measurements, noise can be averaged and allows reducing the operating voltage to less than 30V. Therefore we developed a multi-sensor front-end for low voltage operation of arrays.

Cabling / Connectors

Typically conventional array probes require one channel per element. Some systems operate multiplexed/ de-multiplexed groups of elements in certain modes to improve speed and reduce cabling.

For our case the principle of ultrasonic wave superposition has been exploited to achieve the maximum physical imaging capability while minimising the number of simultaneously operating channels. Therefore we maximised the extent of multiplexing/de-multiplexing in the low-voltage multi-sensor front end. With this front end it is then possible to run several hundreds of sensors on a single bus, called daisy chain, with which nearly every reasonable topology of sensor positioning is possible. A whole set of sensor elements is then connected to a serial sensor element interface with a minimum cabling that is necessary to connect to the driving electronics. The multi-sensor front-end allows to cascade several sets of sensors in one or, if redundancy is required in several lines.

Equipment Hardware

Conventional imaging ultrasound equipment extensively requires analogue electronics hardware to interface to sensors, filter and amplify, filter and analyse, drive and trigger sources for a large number of channels. Typically the hardware cost is huge and scales with the number of channels and performance of each channel. In our case where there is no real-time feedback requirement, one single channel is sufficient to operate the whole network of sensor elements while after all providing the maximum physical result of the combination of all sensor systems. In conventional terms: Despite using only one channel, the capability of focussing, zooming, steering, etc. – is fully available, but at a drastically lower cost.

Additionally it is now possible to try also combinations of sensing techniques: strain gauges, acoustic emission sensors, temperature sensors, etc.

Further more, since the amount of electronics, necessary to run the network is minimised it seems feasible to integrate all electronics to the structure with a low-power infrastructure.

Risks ?

Yes! The prototype results of above mentioned developments have been used to demonstrate the feasibility of a low-power operation of imaging ultrasound sensor networks. A combination of numerous mathematical and physical tricks is exploited to achieve low-cost hardware and improve ease of installation. But the integration of such electronics to the actual structure is still a challenging technological issue in terms of bonding, embedding?, encapsulation, interfacing, etc. under lifetime conditions.

Little experience is available whether the structural integration of low-power electronics on military platforms is possible in a way to achieve the reliability and robustness required for military platforms. However, if we can fully exploit the potential of miniaturisation as shown above we can achieve improved practicability and reliability.

SUMMARY

For the example of integrating a low-power ultrasound sensor element network for the purpose of imaging damage in the structure of military platforms we have demonstrated the exploitation of permanent sensor installation to improve the practicability of sensor-based built-in damage detection to replace conventional ultrasound phased array inspections. By eliminating major draw-backs of conventional phased array technology in terms of practicability as built-in damage detection, we keep the powerful capabilities of phased array ultrasound and can rely on the expertise of a well-appreciated community of phased-array users.

Nevertheless, for an introduction of low-power electronics networks to military platform structures numerous technological aspects still need to be discussed and further developed, especially the potential of new integration methods needs to be evaluated.

CONCLUSION

The technological potential of low-power sensor applications now seems to extend to applications where previously high-power hardware had to be used exclusively. Practicability in terms of weight, space and cost is expected to improve tremendously, if low-power electronics work can be integrated to the structure, which is likely, but not certain. Miniaturised structural integration technologies should be developed further to broaden military platforms capabilities at affordable cost.

REFERENCES

[1] Kress, K.-P. [2003], “Overview on the AHMOS project”, keynote lecture, 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[2] Tikka, J. [2003] “Strain Gauge Capabilities in Crack Detection”, 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[3] McGugan, M.. [2003] "Improving the Structural Testing of Wind Turbine Blades by Monitoring Acoustic Emission", 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[4] Read, I. [2003], "Automated Notification of Structural Damage for Structural Health Management Using Acoustic Emission Detection", 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[5] Hedman, R [2003] "Embedded Microcontroller Based Networked Measurement and Analysis System with Strain Gages Tailored to Fatigue Crack Detection", 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[6] Guemes, A. [2003] "Embedded Fibre Bragg Gratings for Damage Detection in Composites", 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[7] Kress, K.-P. [2003] "Integrated Imaging Ultrasound (SWISS)", 4th International Workshop on Structural Health Monitoring IWSHM, Stanford 2003

[8] Kress, K.-P.; Dittrich,K.; Guse,G. [2001], "Smart Wide area Imaging Sensor System (SWISS)", SPIE Conference on Smart Structures, Newport 2001; paper 4332-62

[9] Kress, K.-P., H.-J. Baderschneider, G. Guse [2003], "Imaging Ultrasonic Sensor System SWISS Completed 60.000 Simulated Flight Hours to Check Structural Integrity of Aircraft Subcomponent", SPIE Conference on Smart Structures, San Diego 2003, paper 5046-39

SYMPOSIA DISCUSSION – PAPER NO: 8

Author's Name: K.-P. Kress

Question:
What is resolution limit and can a closed crack be observed?

Author's Response:
Closed cracks are more difficult to detect due to the reduced ultrasound reflection. Detectability is comparable with conventional ultrasound. The resolution is limited by the ultrasound wavelength, if the number of sensors is high enough.

Question (Mr Banks):
100 element array, 80 dB gain, is it coherent gain?

Author's Response:
The signal processing not necessarily requires phase coherence, but in almost all cases it is used to achieve optimum quality of the resulting images. Example: for a linear 100 sensors array, the maximum gain is about 100 squared or 40 dB amplitude / 80 dB energy.